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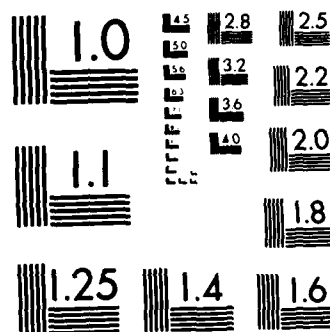
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THESIS

INTERACTIVE COMPUTER PROGRAM
FOR THE
ANALYSIS AND DESIGN OF LINEAR
TIME INVARIANT SYSTEMS

by

Habib Ismail
December 1984

Thesis Advisor:

G. J. Thaler

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Design of control systems by classical methods being essentially a repetitive, trial and error procedure, this program greatly cuts down the turn around time and leads to faster, more satisfactory results.

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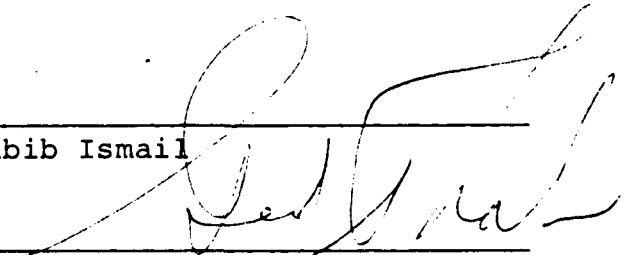
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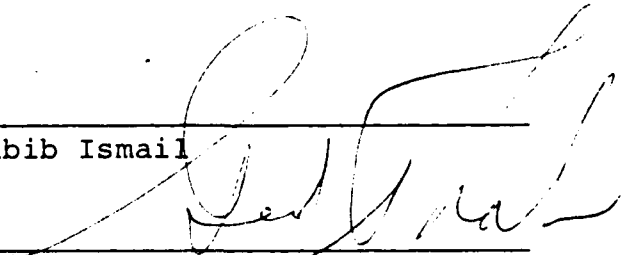
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B.E., University of Karachi, Pakistan, 1974

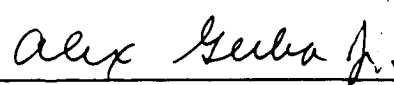
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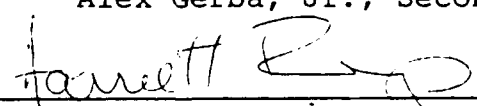
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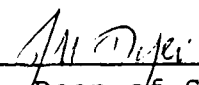

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ABSTRACT

In this thesis, an interactive computer program for the analysis and design of time invariant unity feedback, ^{linear} control systems is presented, using cascade or feedback or both types of compensation.

By using this program, the user is freed from the tedious, time consuming and error prone method of hand calculations, letting the computer handle these tasks efficiently and speedily. The user can then concentrate fully on the placement of poles and zeroes of the compensator(s) used.

Design of control systems by classical methods being essentially a repetitive, trial and error procedure, this program greatly cuts down the turn around time and leads to faster, more satisfactory results.

*Additional features:
1. Transfer function to state space conversion
2. Root locus plot*

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I. INTRODUCTION

During the past two decades, the scientific and engineering communities have witnessed an ever increasing role of the digital computer in the fields of research, development and analysis of systems. The computer, today, is being used to solve engineering problems, whose solution, until very recently required long and tedious procedures. Still, it is probably true that this machine has potential not fully recognized yet, which is why the attention of so many computer scientists/engineers is focused on devising more efficient and innovative operating procedures.

Control system design is one area where classical theory has been extensively developed and used. It is fair to say that even today, most analysis and design problems of linear, time invariant control systems can still be approached using the methods developed by Bode, Nyquist and others.

A totally new approach to the design of control systems became available with the development of optimal control theory and the state variable analysis. These methods have been intensively developed in the last 10-15 years, but now their weaknesses have been exposed too. The "states" of the plant may not necessarily represent physically measurable quantities, and consequently it may not be possible to

implement the results at all. Luenberger's observers, designed to overcome this problem, can at best provide estimates of the state trajectory. Furthermore, the optimal control approach to design relies very heavily on mathematical manipulation, providing little insight to the actual working of the plant; the only input of the designer being the form of the cost function.

An intelligent use of the speed and information processing ability of the digital computer, coupled with the reliable features of classical theory appear to be the best solution to the problem at hand. The classical approach to design, being essentially a trial and error method, if the order of the system is fairly high, the number of repetitive calculations and the time required to perform these calculations becomes prohibitively large, the assistance of the computer in such problems becomes indispensable.

The work in this thesis was to develop an interactive, user oriented computer program that would prompt the user to input the transfer function and cascade/feedback compensators. The program would then display on the IBM 3277 - Tektronix 618 dial screen terminals the Bode Plot of both magnitude and phase. The program could be repeatedly used, with the user having the option to change/modify the compensators, each time viewing the effect of his modifications on the screen until he arrives at a satisfactory solution.

II. CONTROL ENGINEERING ANALYSIS

A. GENERAL

A continuous time control system may be represented in one of the following forms:

- a. Transfer functions
- b. State equations
- c. System block diagrams or signal flow graphs

Algorithms exist in almost every undergraduate control engineering text to convert the system representation from one given form to another. Gianniotis (Ref. 1) describes a simple method of converting from transfer function to state variable form in Chapter II.

The transfer function representation in its most general form is:

$$\frac{A_m S^m + A_{m-1} S^{m-1} + A_{m-2} S^{m-2} + \dots + A_0 S^0}{B_n S^n + B_{n-1} S^{n-1} + B_{n-2} S^{n-2} + \dots + B_0 S^0}$$

Usually the mathematical description of the system is found in the transfer function form in the literature. Analysis and design of control systems by classical methods also requires the representation of the system in this form.

Table 1. (Contd.)

0.464157E+01	-0.480013E+01	-0.100608E+03
0.514174E+01	-0.636283E+01	-0.103974E+03
0.569579E+01	-0.788934E+01	-0.107576E+03
0.630955E+01	-0.944906E+01	-0.111432E+03
0.693945E+01	-0.110539E+02	-0.115540E+03
0.774261E+01	-0.127110E+02	-0.119885E+03
0.857692E+01	-0.144313E+02	-0.124433E+03
0.950116E+01	-0.162196E+02	-0.129133E+03
0.105250E+02	-0.180814E+02	-0.133930E+03
0.115591E+02	-0.200195E+02	-0.138782E+03
0.129155E+02	-0.220340E+02	-0.143812E+03
0.143072E+02	-0.241230E+02	-0.148909E+03
0.158469E+02	-0.262850E+02	-0.154003E+03
0.175507E+02	-0.285134E+02	-0.159174E+03
0.194485E+02	-0.308033E+02	-0.164335E+03
0.215443E+02	-0.331480E+02	-0.169576E+03
0.238658E+02	-0.355431E+02	-0.174897E+03
0.264375E+02	-0.379807E+02	-0.180212E+03
0.292863E+02	-0.404556E+02	-0.185516E+03
0.324421E+02	-0.429623E+02	-0.190802E+03
0.359380E+02	-0.454962E+02	-0.196067E+03
0.398106E+02	-0.480529E+02	-0.201304E+03
0.441004E+02	-0.506288E+02	-0.206519E+03
0.488526E+02	-0.532208E+02	-0.211715E+03
0.541167E+02	-0.558260E+02	-0.216892E+03
0.599483E+02	-0.584423E+02	-0.222050E+03
0.664080E+02	-0.610677E+02	-0.227180E+03
0.735639E+02	-0.637005E+02	-0.232281E+03
0.814910E+02	-0.663395E+02	-0.237354E+03
0.902722E+02	-0.689835E+02	-0.242408E+03
0.999998E+02	-0.716317E+02	-0.247444E+03

Table 1. Tabular Output of Example 4.1

FREQ	MAGNITUDE	PHASE
0.100000E-01	0.539790E+02	-0.901134E+02
0.110770E-01	0.530907E+02	-0.901258E+02
0.122712E-01	0.522019E+02	-0.901395E+02
0.135936E-01	0.513130E+02	-0.901546E+02
0.150584E-01	0.504242E+02	-0.901714E+02
0.166810E-01	0.495354E+02	-0.901900E+02
0.184785E-01	0.486466E+02	-0.902106E+02
0.204697E-01	0.477579E+02	-0.902335E+02
0.226754E-01	0.468691E+02	-0.902588E+02
0.251188E-01	0.459804E+02	-0.902868E+02
0.278256E-01	0.450918E+02	-0.903179E+02
0.308240E-01	0.442032E+02	-0.903524E+02
0.341455E-01	0.433146E+02	-0.903905E+02
0.378249E-01	0.424262E+02	-0.904329E+02
0.419008E-01	0.415378E+02	-0.904798E+02
0.464158E-01	0.406490E+02	-0.905318E+02
0.514175E-01	0.397615E+02	-0.905890E+02
0.569580E-01	0.388736E+02	-0.906536E+02
0.630950E-01	0.379859E+02	-0.907247E+02
0.698946E-01	0.370985E+02	-0.908036E+02
0.774263E-01	0.362114E+02	-0.908913E+02
0.857695E-01	0.353247E+02	-0.909887E+02
0.950117E-01	0.344385E+02	-0.910972E+02
0.105250E+00	0.335529E+02	-0.912180E+02
0.116391E+00	0.326680E+02	-0.913520E+02
0.129155E+00	0.317841E+02	-0.915030E+02
0.143072E+00	0.309012E+02	-0.916711E+02
0.158489E+00	0.300196E+02	-0.918595E+02
0.175567E+00	0.291397E+02	-0.920711E+02
0.194486E+00	0.282617E+02	-0.923094E+02
0.215443E+00	0.273860E+02	-0.925787E+02
0.238658E+00	0.265130E+02	-0.928840E+02
0.264370E+00	0.256433E+02	-0.932318E+02
0.292864E+00	0.247775E+02	-0.936298E+02
0.324421E+00	0.239162E+02	-0.940870E+02
0.359381E+00	0.230600E+02	-0.946171E+02
0.398106E+00	0.222090E+02	-0.95234E+02
0.441004E+00	0.213655E+02	-0.959547E+02
0.488526E+00	0.205278E+02	-0.968035E+02
0.541168E+00	0.196960E+02	-0.978075E+02
0.599483E+00	0.188709E+02	-0.989995E+02
0.664081E+00	0.180487E+02	-0.100417E+03
0.735840E+00	0.172265E+02	-0.102103E+03
0.814911E+00	0.163984E+02	-0.104101E+03
0.902723E+00	0.155561E+02	-0.106450E+03
0.999999E+00	0.146882E+02	-0.109181E+03
0.110775E+01	0.137807E+02	-0.112300E+03
0.122712E+01	0.128181E+02	-0.115784E+03
0.135935E+01	0.117855E+02	-0.119567E+03
0.150583E+01	0.106723E+02	-0.123548E+03
0.166809E+01	0.947399E+01	-0.127800E+03
0.184785E+01	0.819452E+01	-0.133594E+03
0.204696E+01	0.684498E+01	-0.140427E+03
0.226754E+01	0.544112E+01	-0.149035E+03
0.251188E+01	0.399998E+01	-0.159404E+03
0.278255E+01	0.253084E+01	-0.172561E+03
0.308239E+01	0.106322E+01	-0.188567E+03
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0.378247E+01	-0.189173E+01	-0.154429E+03
0.419007E+01	-0.337225E+01	-0.157444E+03

EXAMPLE 4.1 LEAD COMPENSATION

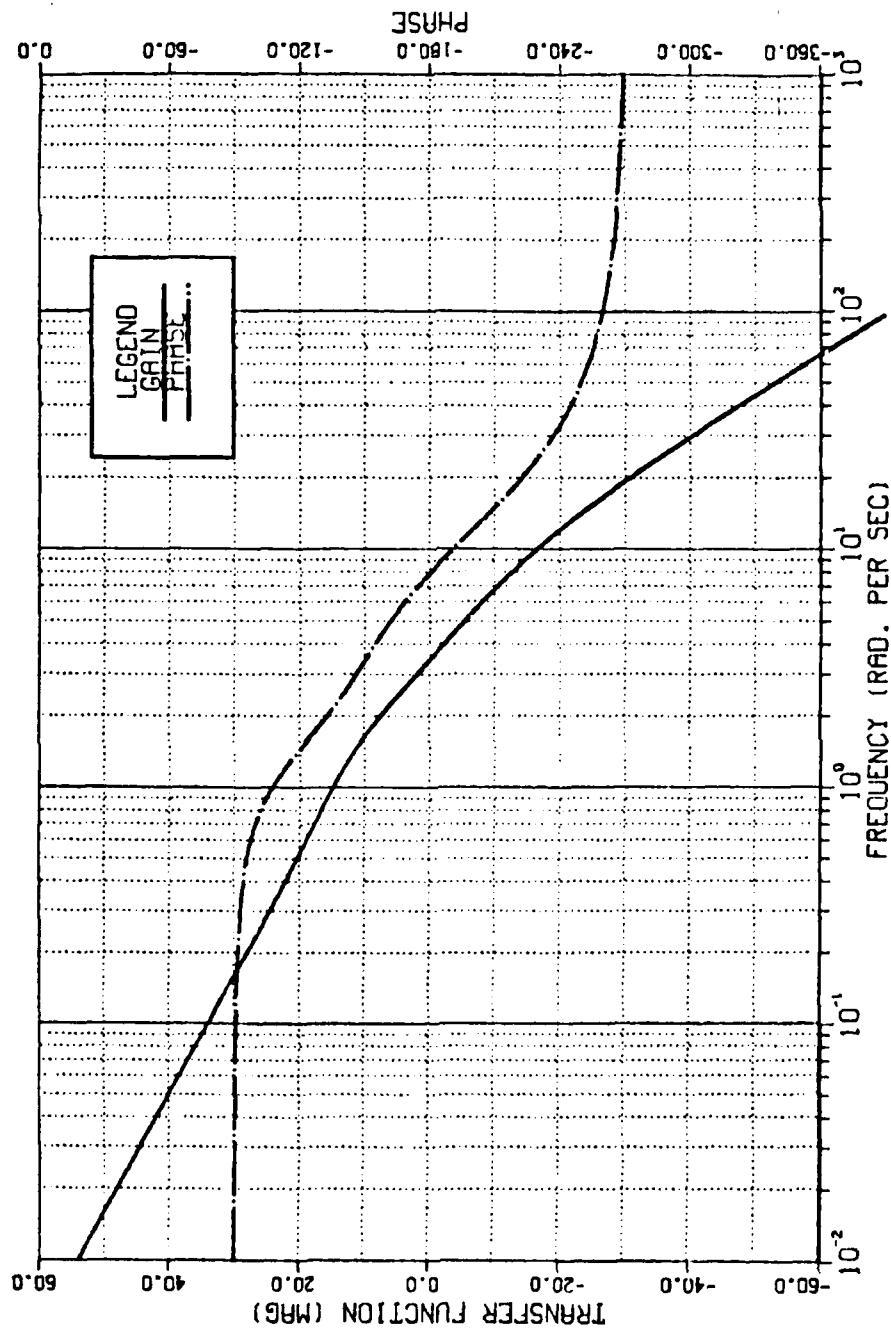


Figure 3. Lead Compensation Bode Plot of Example 4.1

EXAMPLE 4.1 UNCOMPENSATED SYSTEM

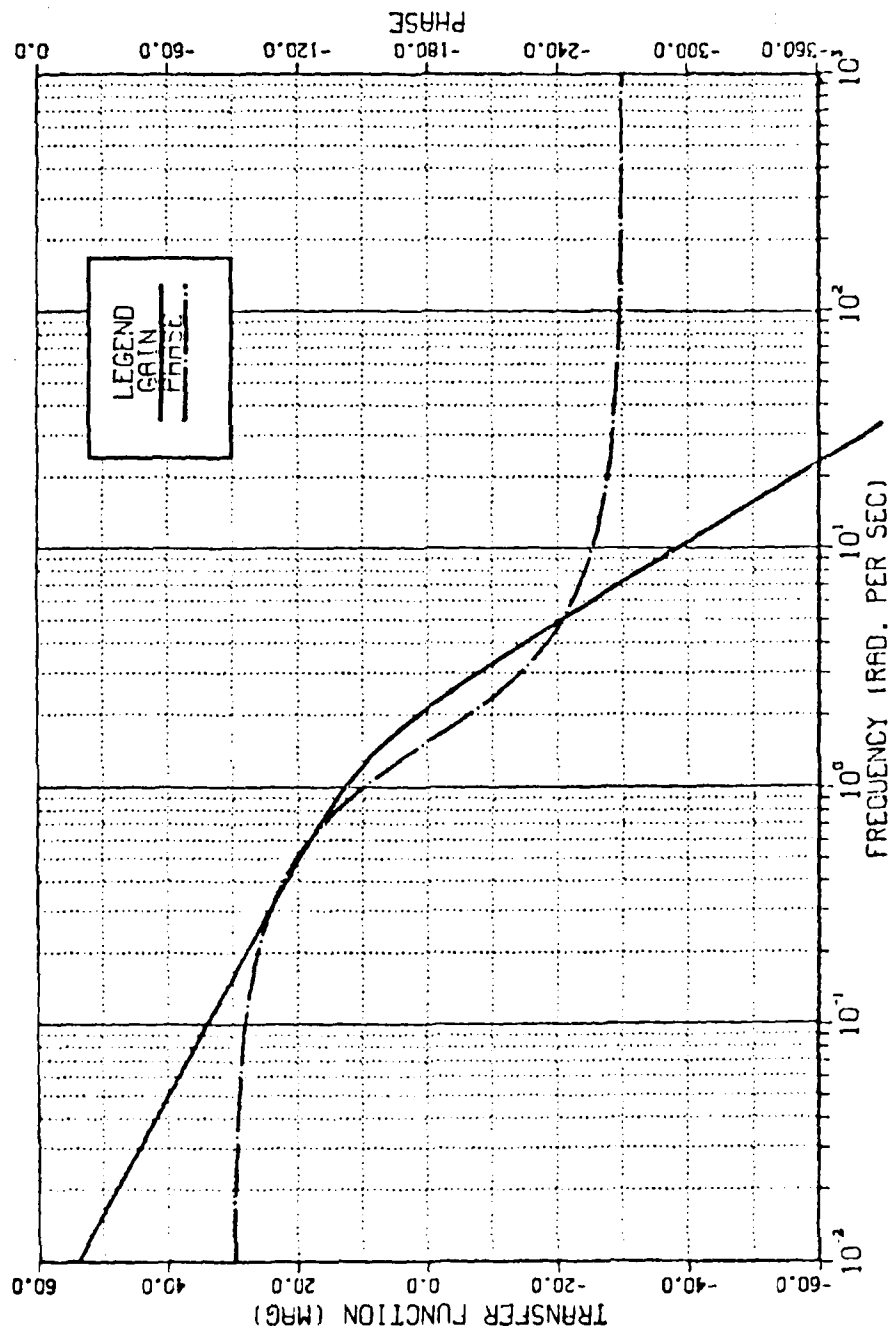


Figure 2. Uncompensated Bode Plot of Example 4.1

The velocity constant is not to be decreased. Design a phase lead compensator which will provide M_{pw} less than 1.5.

b. Solution

The first step is to get the transfer function in the required form:

$$G(s) = \frac{5.0}{0.21s^3 + 1.0s^2 + 1.0s} \quad (4.2)$$

The Bode Plot of the uncompensated system drawn using the program is shown on figure 2 and the tabular output on table 1. The uncompensated system has a phase margin of -20 degrees. To achieve a M_{pw} less than 1.5, a phase margin of 44 degrees or more is required. Approximately 64 degrees of positive phase shift are therefore needed. Two sections of lead filter are introduced as given below:

$$G_c = \frac{(s/3.0 + 1)(s/1.5 + 1)}{(s/10.0 + 1)^2}$$

The compensated Bode Plot is given on figure 3 showing a phase margin of 35 degrees.

It may be pointed out that the final values for the lead filter poles and zeroes were arrived at after 3 iterations and this design problem was solved in less than 15 minutes.

IV. PROGRAM PERFORMANCE INVESTIGATION

A. GENERAL

The program was tested by solving several linear control system design problems. Very satisfactory results were obtained in all cases with remarkable efficiency and speed. The only necessary condition is proper problem formulation. This is true for any interactive computer program. Once the program is used a couple of times, the user gets the necessary familiarity with its working.

The example problems presented below are used to demonstrate the performance and capabilities of the program. The examples can also help the user in formulating his own particular problem. The examples were selected from Thaler's 'Design of Feedback Systems' (Ref. 2)

B. EXAMPLE PROBLEMS

1. Example 4.1 : A Phase Lead Network

a. Problem Statement

A positioning system is single loop with unity feedback and forward transfer function

$$G(s) = \frac{5.0}{s(0.7s + 1)(0.3s + 1)}$$

TITLES inputs the two lines of text as headings for the Bode Plot.

In addition, the main program handles the tasks of displaying the tabular output and the Bode Plot of the open and closed loop response of the system as required.

C. PROGRAM DESCRIPTION

The main program is the coordination center which controls the calling of the supporting subroutines, in order to input the transfer function, cascade/feedback compensators and other necessary information. The tabular results and the Bode Plot are then displayed on the two screens respectively.

The main program as well as the accompanying subroutines can be found in Appendix A. They contain a sufficient number of comment cards to be self explanatory.

The following is a brief description of the performance and purpose of the various subroutines.

NUMER inputs the numerator of the plant transfer function.

DENOM inputs the denominator of the plant transfer function.

CASCAD inputs up to 6 first order lead/lag filters.

SECAS inputs the numerator of the second order band pass/band stop filter.

SECASD inputs the denominator of the second order filter.

FETCH determines the value of the radial frequency, w , at the origin of the x-axis.

DECADE determines the number of decades of frequency to be spanned.

FEEDBK inputs the various parameters of feedback compensators.

In brief, the whole BODPLT package works as follows:
A user, logged into the VM/CMS environment of the system from the dual screen terminals, issues the command DISSPLA BODPLT. The package then assumes control. The program begins its execution by interrogating the user and calling the appropriate subroutine accordingly. All programmer-composed subprograms are included in the main program titled BODPLT FORTRAN.

The BODPLT program has the following important features:

- runs of the VM/CMS time sharing system.
- interrogates the user in entering all problem specifications from the terminal.
- can handle up to a ninth order plant transfer function, six first order and one second order cascade filters.
- prompts the user to input the parameters of velocity feedback, acceleration feedback or approximate acceleration feedback as required.
- provides the solution in tabular form on the IBM 3277 screen and the Bode Plot on the TEK 618 terminal.
- can provide hard copy version of the problem specifications and tabular output by using the RECORD ON/RECORD OFF execs, and of the BODE PLOT on the Tektronix printer where installed.
- allows problem specifications to be changed between runs.

III. PROGRAMMING CONSIDERATIONS

A. GENERAL

Any interactive software package, such as the one developed in this thesis must provide a simple yet unambiguous means of data input and output. The data must be easy to interpret and apply to the problem at hand. Programs producing highly satisfactory results but requiring long studying time and/or special programming skills are of limited use only.

The intent of this thesis is to present such a program, Computer Aided Design of Linear Systems. Special care has been taken to develop the program so that the user has to invest very little time learning to use it.

B. MAIN FEATURES OF THE PROGRAM

The development of a user oriented interactive computer program in solving engineering problems requires a considerable amount of programming work, contributing significantly to its complexity and size.

The computer program, hereafter referred to as BODPLT consists of a main program, a number of programmer-composed subroutines, a few library functions/subroutines, and various subroutines of the DISSPLA graphics package. The entire program is written in the FORTRAN IV language.

It was found on the average that turn around time for a typical third order system with two cascade compensators is less than five minutes.

Cascade compensation may further be classified into two further types; a high pass filter usually called a phase lead compensator, and a low pass or phase lag compensator.

The selection of the type of compensator(s) to be used depends on a number of factors, the important ones being experience, personal preferences, availability, system constraints, etc. Unfortunately, there are no mathematical techniques to help in this selection process. Generally, one has to complete several designs and then choose the most appropriate one.

C. COMPUTER AIDED DESIGN

Of all the classical design methods available, the Bode diagram technique is generally considered to be the simplest, at the same time providing the most insight into system performance and behavior. The Bode design method may be used equally effectively both with cascade and feedback compensation schemes.

The computer program developed in this thesis displays on the terminal, initially, the Bode diagram (magnitude and phase) of the uncompensated open loop system. The user may then select the type of compensator to be used, and feed this information to the computer. The display changes, now showing the compensated system Bode Plot. This procedure may be repeated iteratively, with the computer updating the Bode Plot with each change made.

Compensators used in the design of feedback control systems are generally classified as shown in the block diagrams of figure 1.

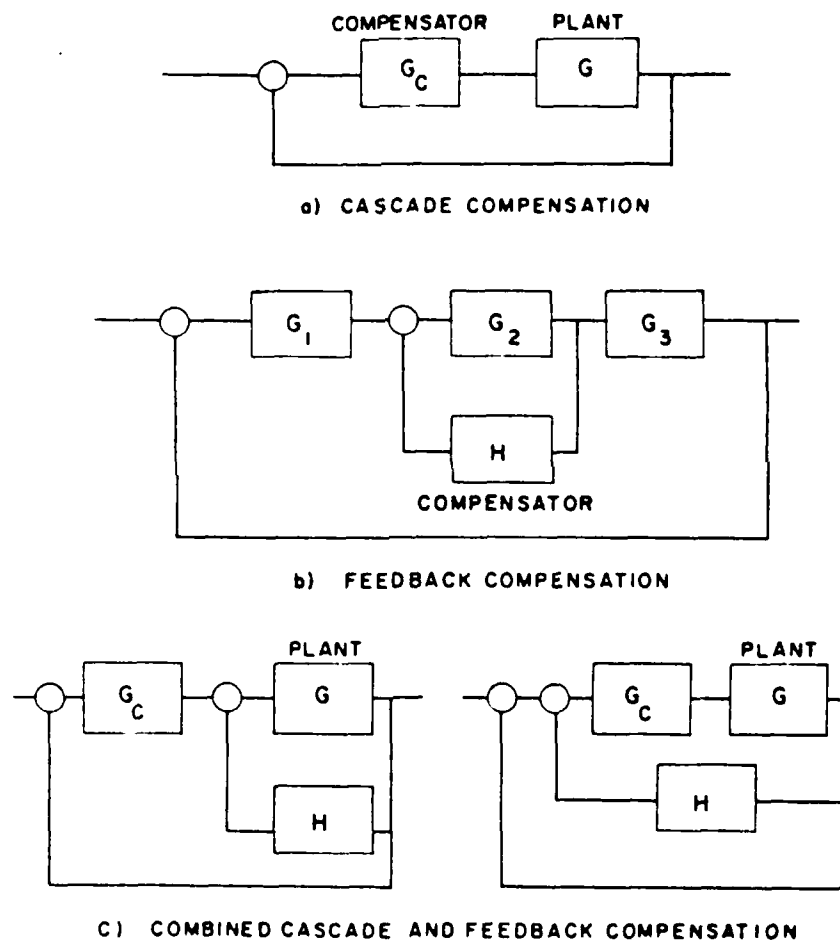


Figure 1. Classification of Compensation Structures

This thesis does not address the problem of converting from one form of representation to another. It is assumed that any conversions necessary have already been performed and that the system is represented by its open loop transfer function.

B. PROBLEM FORMULATION

Each system design has its own unique characteristics, but in general the system has to meet some kind of performance standards. These performance standards are generally provided as numerical specifications. The first step in the design of a control system is to analyze the system by itself in the usual feedback loop configuration. This is usually referred to as the uncompensated system.

Analysis of the uncompensated system almost always shows that the system cannot meet some or all of the given performance standards. Usually, additional components have to be inserted in the system for the purpose of altering the performance of the system. These components are called compensators. Compensation is a two step procedure, in which additional components (compensators) are inserted to change the structure of the system, and these components are then adjusted until the performance characteristics are satisfied.

The theory of cascade and feedback compensation is discussed in detail by Thaler (Ref. 2) in Chapters 5 and 6. Only a brief discussion of the types of compensators is presented here.

EXAMPLE 4.2 UNCOMPENSATED SYSTEM

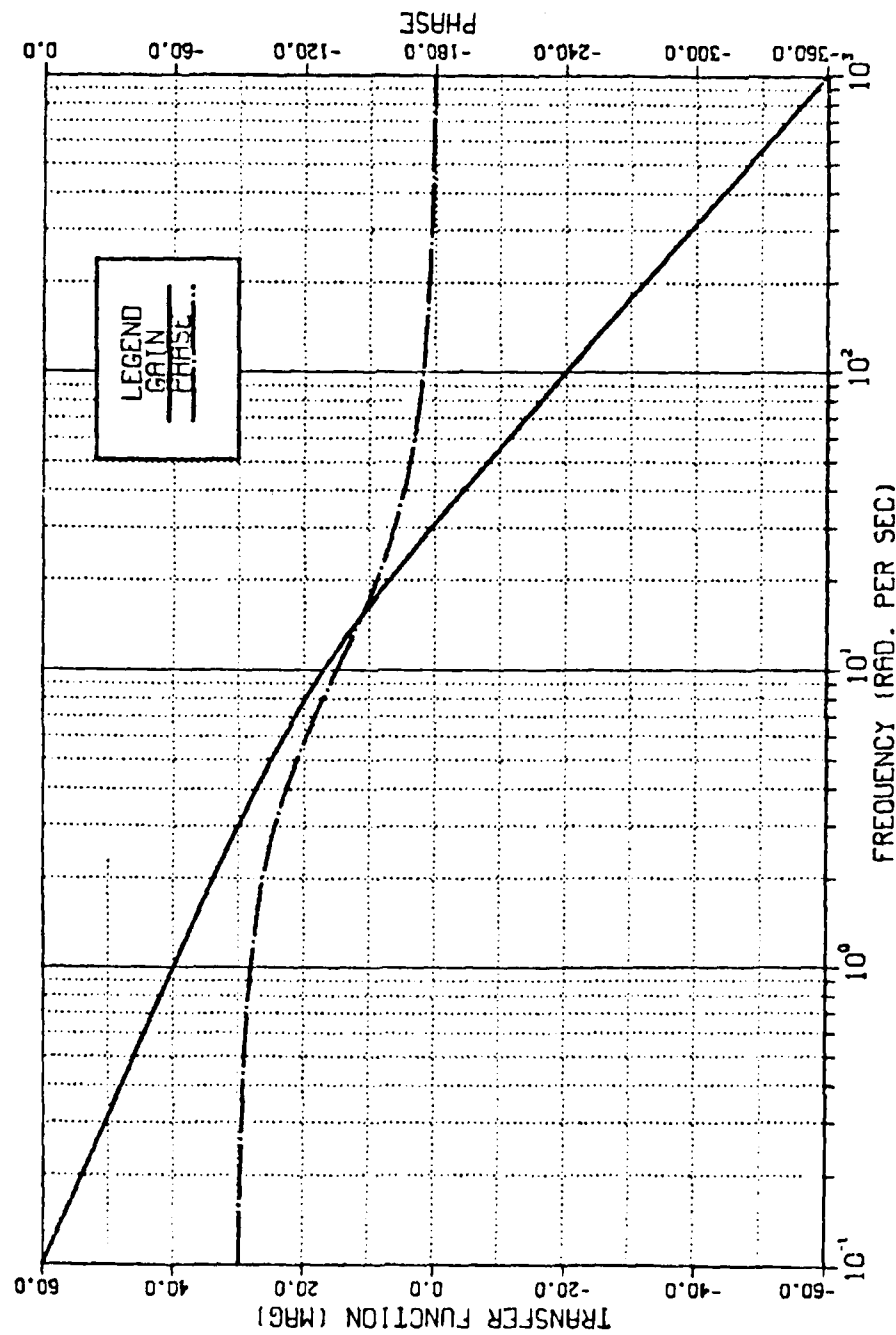


Figure 4. Uncompensated Bode Plot of Example 4.2

EXAMPLE 4.2 LAG/LEAD COMP.

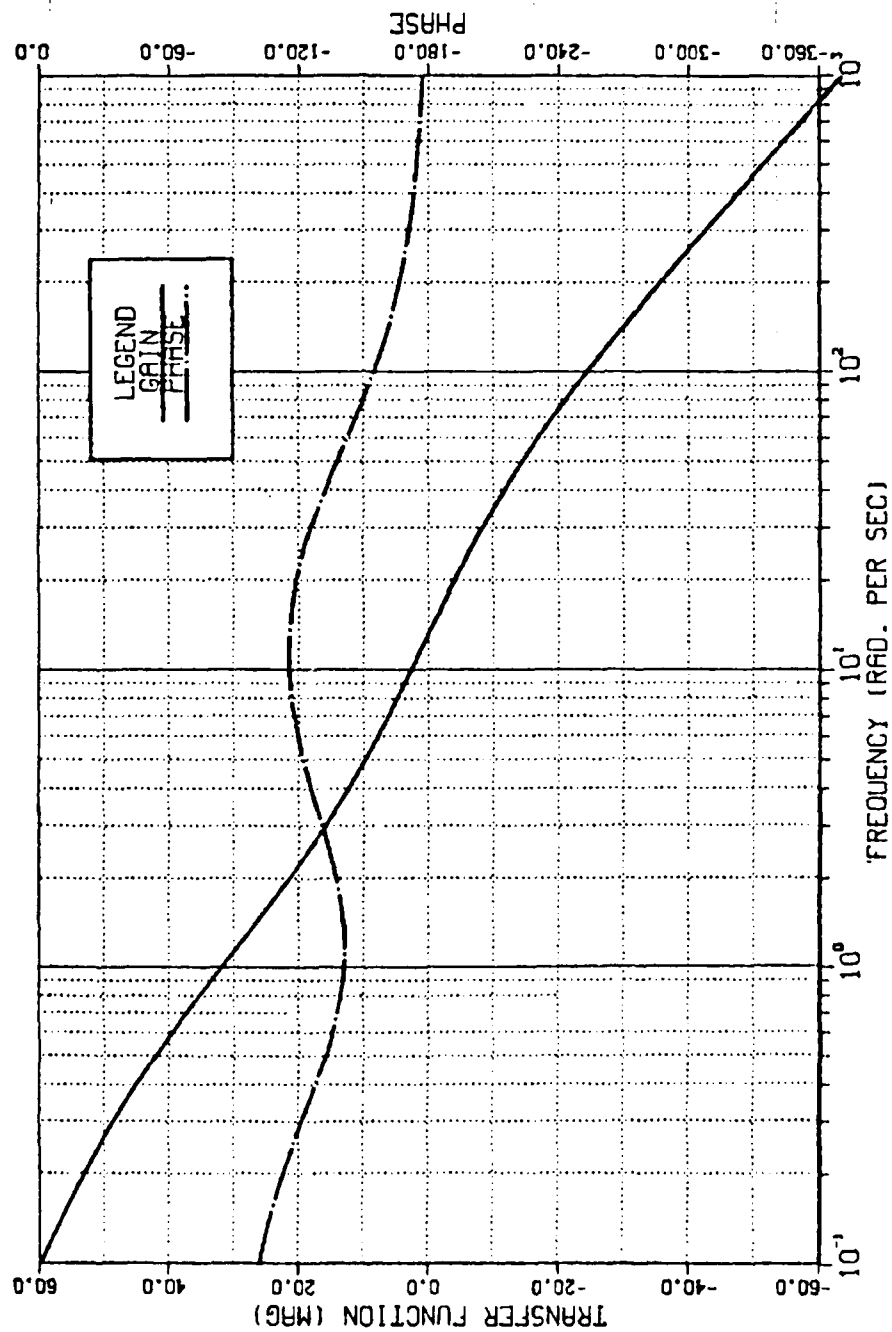


Figure 5. Lag/Lead Compensation in Example 4.2

Table 2. Tabular Output of Example 4.2

FREQ	MAGNITUDE	PHASE
0.100000E+00	0.598345E+02	-0.995141E+02
0.110776E+00	0.589089E+02	-0.100303E+03
0.122712E+00	0.579754E+02	-0.101580E+03
0.135935E+00	0.570325E+02	-0.102769E+03
0.150584E+00	0.560783E+02	-0.104058E+03
0.166810E+00	0.551106E+02	-0.105457E+03
0.184785E+00	0.541270E+02	-0.106968E+03
0.204697E+00	0.531249E+02	-0.108594E+03
0.226754E+00	0.521012E+02	-0.110331E+03
0.251188E+00	0.510529E+02	-0.112174E+03
0.278256E+00	0.499765E+02	-0.114115E+03
0.308240E+00	0.488687E+02	-0.116138E+03
0.341454E+00	0.477266E+02	-0.118226E+03
0.378248E+00	0.465474E+02	-0.120353E+03
0.419008E+00	0.453289E+02	-0.122491E+03
0.464158E+00	0.440698E+02	-0.124600E+03
0.514175E+00	0.427697E+02	-0.126683E+03
0.569580E+00	0.414292E+02	-0.128623E+03
0.630956E+00	0.400502E+02	-0.130449E+03
0.698946E+00	0.386356E+02	-0.132106E+03
0.774263E+00	0.371891E+02	-0.133500E+03
0.857695E+00	0.357155E+02	-0.134785E+03
0.950117E+00	0.342201E+02	-0.135758E+03
0.105250E+01	0.327090E+02	-0.136401E+03
0.116591E+01	0.311881E+02	-0.136884E+03
0.129155E+01	0.296640E+02	-0.137022E+03
0.143072E+01	0.281432E+02	-0.136877E+03
0.158469E+01	0.266320E+02	-0.136457E+03
0.175567E+01	0.251367E+02	-0.135775E+03
0.194485E+01	0.236631E+02	-0.134853E+03
0.215443E+01	0.222164E+02	-0.133716E+03
0.238658E+01	0.208014E+02	-0.132395E+03
0.264375E+01	0.194217E+02	-0.130927E+03
0.292864E+01	0.180801E+02	-0.129351E+03
0.324421E+01	0.167783E+02	-0.127709E+03
0.359381E+01	0.155166E+02	-0.126043E+03
0.398106E+01	0.142947E+02	-0.124393E+03
0.441004E+01	0.131107E+02	-0.122797E+03
0.488526E+01	0.119624E+02	-0.121289E+03
0.541168E+01	0.108466E+02	-0.119899E+03
0.599483E+01	0.975994E+01	-0.118652E+03
0.664081E+01	0.869860E+01	-0.117569E+03
0.735640E+01	0.765877E+01	-0.116666E+03
0.814911E+01	0.663658E+01	-0.115955E+03
0.902723E+01	0.562823E+01	-0.115445E+03
0.999999E+01	0.463006E+01	-0.115145E+03
0.110775E+02	0.363853E+01	-0.115060E+03
0.122712E+02	0.265011E+01	-0.115192E+03
0.135935E+02	0.166130E+01	-0.115547E+03
0.150583E+02	0.663658E+00	-0.116125E+03
0.166809E+02	-0.331396E+00	-0.116927E+03
0.184784E+02	-0.134252E+01	-0.117953E+03
0.204696E+02	-0.236847E+01	-0.119201E+03
0.226754E+02	-0.341315E+01	-0.120600E+03
0.251188E+02	-0.448058E+01	-0.122343E+03
0.278255E+02	-0.557482E+01	-0.124219E+03
0.308239E+02	-0.669992E+01	-0.126281E+03
0.341454E+02	-0.785960E+01	-0.128510E+03
0.378247E+02	-0.905738E+01	-0.130883E+03
0.419007E+02	-0.102961E+02	-0.133373E+03

Table 2. (Contd.)

0.404157E+C2	-0.115780E+02	-0.135950E+03
0.514174E+C2	-0.129043E+02	-0.138581E+03
0.569579E+02	-0.142753E+02	-0.141232E+03
0.630955E+C2	-0.156905E+02	-0.143871E+03
0.698945E+02	-0.171484E+02	-0.146467E+03
0.774261E+02	-0.186466E+02	-0.148993E+03
0.857692E+02	-0.201822E+02	-0.151427E+03
0.950116E+02	-0.217522E+02	-0.153749E+03
0.105250E+C3	-0.233526E+02	-0.155948E+03
0.116591E+03	-0.249806E+02	-0.158014E+03
0.129155E+03	-0.266322E+02	-0.159944E+03
0.143072E+C3	-0.283043E+02	-0.161738E+03
0.158489E+03	-0.299941E+02	-0.163392E+03
0.175567E+03	-0.316988E+02	-0.164917E+03
0.194485E+C3	-0.334161E+02	-0.166316E+03
0.215443E+03	-0.351439E+02	-0.167597E+03
0.238658E+C3	-0.366805E+02	-0.168765E+03
0.264375E+C3	-0.386245E+02	-0.169830E+03
0.292863E+03	-0.403745E+02	-0.170798E+03
0.324421E+C3	-0.421296E+02	-0.171678E+03
0.359380E+C3	-0.438888E+02	-0.172476E+03
0.396105E+C3	-0.456513E+02	-0.173199E+03
0.441004E+C3	-0.474166E+02	-0.173854E+03
0.488525E+03	-0.491842E+02	-0.174447E+03
0.541167E+03	-0.509536E+02	-0.174984E+03
0.599482E+C3	-0.527247E+02	-0.175469E+03
0.664080E+03	-0.544969E+02	-0.175907E+03
0.735639E+C3	-0.562702E+02	-0.176304E+03
0.814910E+03	-0.580443E+02	-0.176662E+03
0.902721E+03	-0.598190E+02	-0.176986E+03
0.999958E+C3	-0.615944E+02	-0.177276E+03

3. Example 4.3 : Velocity Feedback

a. Problem Statement

A simple second-order servo is to be compensated with tachometer feedback. The forward transfer function is

$$G(S) = \frac{100.0}{S(S + 1)}$$

and the tachometer transfer function is $K_t S$. The tachometer is fed back around all of the forward gain. Using Bode diagram methods, set K_t to provide $M_{pw} = 1.3$.

b. Solution

Bode Plot for this system is shown on figure 6. The system has a phase margin of about 6 degrees. For $M_{pw} = 1.3$, a phase margin of 45 degrees is required. A rough graphical design on the uncompensated Bode Plot gives

$$1/H = 12.0/S \quad \text{or} \quad H = 0.08S$$

The Bode Plot for the compensated system is on figure 7, showing a phase margin of 50 degrees.

The close loop frequency response of this example, drawn using BODPLT is shown on figure 8.

EXAMPLE 4.3 UNCOMPENSATED SYSTEM

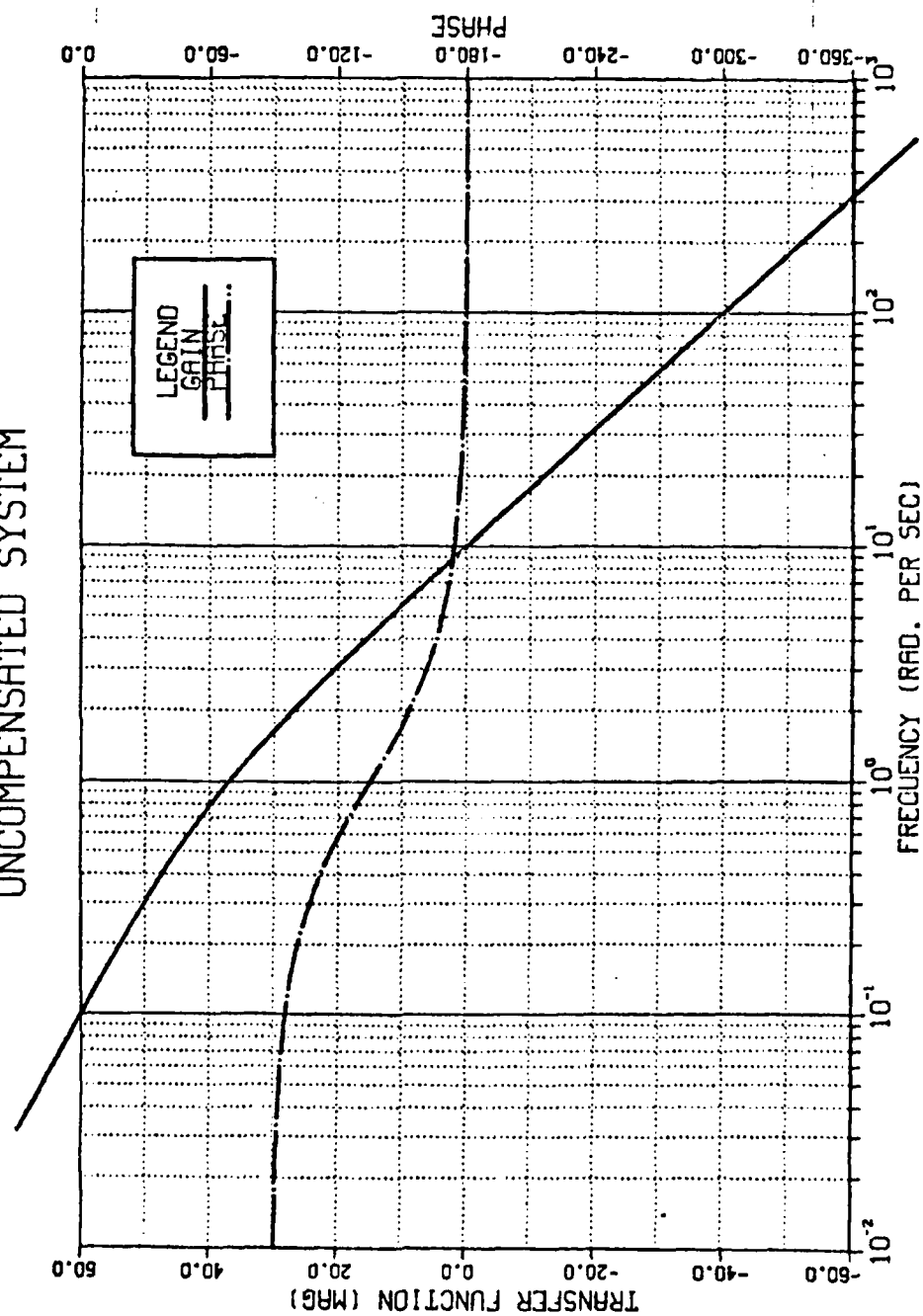


Figure 6. Uncompensated Bode Plot of Example 4.3

EXAMPLE 4.3

VELOCITY FEEDBACK

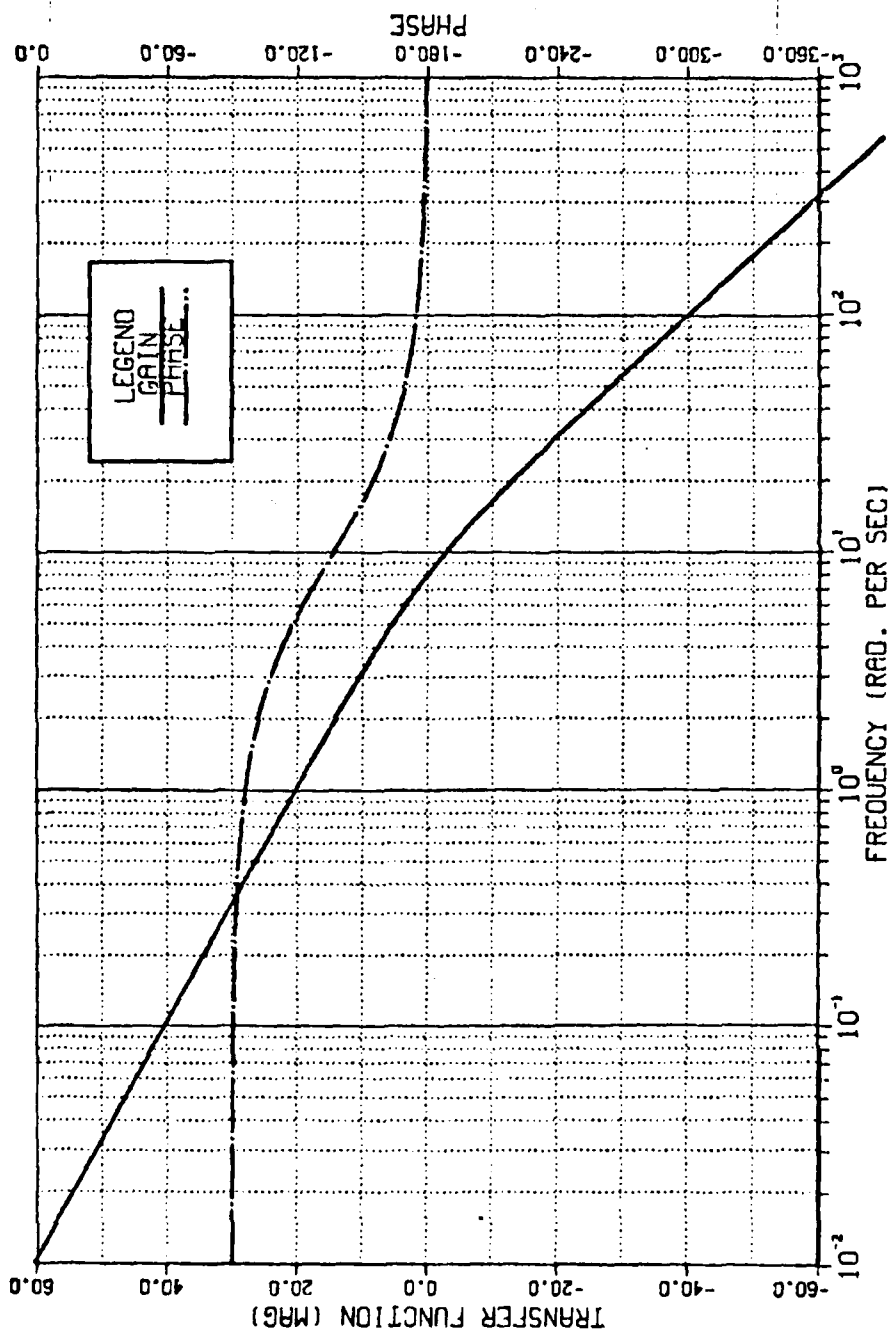


Figure 7. Velocity Feedback Used in Example 4.3

Table 3. Tabular Output of Example 4.3

FREQ	MAGNITUDE	PHASE
0.100000E-C1	0.606303E+02	-C.900604E+02
0.113646E-C1	0.595192E+02	-C.900608E+02
0.129155E-C1	0.584081E+02	-C.900784E+02
0.146780E-C1	0.572970E+02	-C.900892E+02
0.166810E-C1	0.561859E+02	-C.901016E+02
0.189573E-C1	0.550747E+02	-C.901156E+02
0.215443E-C1	0.539636E+02	-C.901310E+02
0.244843E-C1	0.528525E+02	-C.901497E+02
0.278256E-C1	0.517414E+02	-C.901703E+02
0.316227E-C1	0.506303E+02	-C.901936E+02
0.359381E-C1	0.495192E+02	-C.902202E+02
0.408423E-C1	0.484080E+02	-C.902504E+02
0.464159E-C1	0.472969E+02	-C.902848E+02
0.527499E-C1	0.461858E+02	-C.903238E+02
0.599483E-C1	0.450746E+02	-C.903682E+02
0.681291E-C1	0.439635E+02	-C.904185E+02
0.774263E-C1	0.428523E+02	-C.904758E+02
0.879921E-C1	0.417411E+02	-C.905409E+02
0.999958E-C1	0.406298E+02	-C.906149E+02
0.113646E+00	0.395186E+02	-C.906989E+02
0.129155E+00	0.384073E+02	-C.907945E+02
0.146780E+00	0.372959E+02	-C.909030E+02
0.166810E+00	0.361845E+02	-C.910264E+02
0.189573E+00	0.350730E+02	-C.911666E+02
0.215443E+00	0.339613E+02	-C.913259E+02
0.244843E+00	0.328495E+02	-C.915069E+02
0.278255E+00	0.317376E+02	-C.917120E+02
0.316227E+00	0.306253E+02	-C.919463E+02
0.359381E+00	0.295127E+02	-C.922118E+02
0.408423E+00	0.283997E+02	-C.925134E+02
0.464157E+00	0.272862E+02	-C.928500E+02
0.527498E+00	0.261720E+02	-C.932451E+02
0.599483E+00	0.250568E+02	-C.936870E+02
0.681291E+00	0.239404E+02	-C.941886E+02
0.774262E+00	0.228226E+02	-C.947579E+02
0.879919E+00	0.217028E+02	-C.954037E+02
0.999996E+00	0.205804E+02	-C.961360E+02
0.113646E+C1	0.194549E+02	-C.969657E+02
0.129155E+C1	0.183252E+02	-C.979052E+02
0.146779E+C1	0.171902E+02	-C.989675E+02
0.166809E+C1	0.160484E+02	-C.100167E+03
0.189573E+C1	0.148980E+02	-C.101520E+03
0.215443E+C1	0.137367E+02	-C.103042E+03
0.244843E+C1	0.125615E+02	-C.104748E+03
0.278255E+C1	0.113691E+02	-C.106650E+03
0.316227E+C1	0.101552E+02	-C.108778E+03
0.359381E+C1	0.891480E+01	-C.111127E+03
0.408423E+01	0.764222E+01	-C.113708E+03
0.464157E+C1	0.633108E+01	-C.116522E+03
0.527498E+C1	0.497453E+01	-C.119560E+03
0.599482E+C1	0.358567E+01	-C.122804E+03
0.681290E+01	0.209793E+01	-C.126224E+03
0.774261E+01	0.565706E+00	-C.129777E+03
0.879919E+C1	-0.103506E+01	-C.133413E+03
0.999996E+C1	-0.270649E+01	-C.137075E+03
0.113646E+C2	-0.444846E+01	-C.140704E+03
0.129155E+C2	-0.625853E+C1	-C.144242E+03
0.146779E+02	-0.813240E+01	-C.147639E+03
0.166809E+C2	-0.100643E+02	-C.150857E+03
0.189573E+C2	-C.120476E+02	-C.153860E+03

Table 3. (Contd.)

0.215443E+02	-0.140753E+02	-C.156650E+03
0.244843E+C2	-0.161408E+02	-0.159199E+03
0.278255E+C2	-0.182376E+02	-C.161517E+03
0.316226E+02	-0.203602E+C2	-C.163609E+03
0.359380E+C2	-0.225037E+02	-C.165489E+03
0.408423E+02	-0.246639E+02	-C.167170E+03
0.464157E+C2	-0.268375E+02	-0.168668E+03
0.527497E+C2	-C.290217E+02	-0.169999E+03
0.599482E+02	-0.312143E+02	-C.171179E+03
0.681290E+C2	-0.334134E+02	-0.172224E+03
0.774261E+02	-C.356177E+02	-C.173148E+03
0.879919E+02	-0.378259E+C2	-C.173964E+03
0.999595E+C2	-C.400373E+02	-C.174684E+03
0.113646E+03	-C.422511E+02	-C.175319E+03
0.129154E+C3	-0.444668E+02	-0.175679E+03
0.146779E+C3	-0.466840E+02	-0.176372E+03
0.166809E+03	-0.489023E+02	-C.176806E+03
0.189573E+C3	-0.511215E+02	-0.177189E+03
0.215443E+C3	-0.533413E+02	-C.177526E+03
0.244843E+03	-0.555617E+02	-C.177822E+03
0.278255E+C3	-0.577825E+02	-C.178083E+03
0.316226E+C3	-0.600037E+02	-C.178313E+03
0.359379E+C3	-0.622250E+02	-0.178515E+03
0.408422E+C3	-0.644466E+02	-0.178695E+03
0.464157E+03	-0.666683E+02	-C.178850E+03
0.527497E+C3	-0.688902E+02	-0.178988E+03
0.599481E+C3	-0.711121E+02	-C.179109E+03
0.681290E+03	-0.733341E+02	-C.179215E+03
0.774260E+C3	-0.755561E+02	-C.179309E+03
0.879918E+C3	-C.777782E+02	-C.179392E+03
0.999597E+C3	-0.800003E+02	-0.179465E+03

EXAMPLE 4.3 CLOSED LOOP RESPONSE

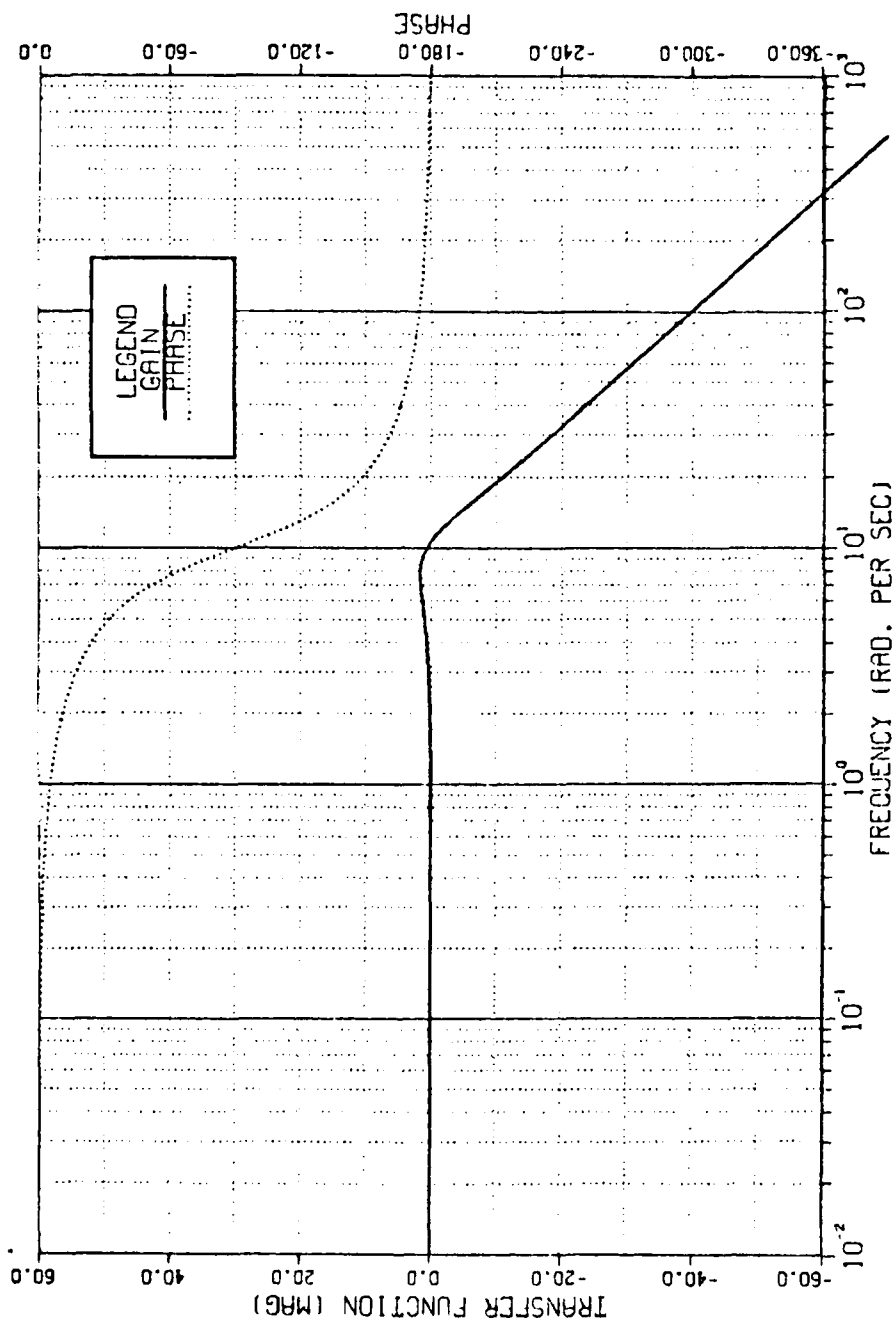


Figure 8. Closed Loop Response of Example 4.3

V. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

The objective of this thesis was to develop an interactive user oriented computer program which would aid in solving control engineering problems using the Bode method of design. The presented program proves that frequency domain design of control systems using the digital computer as an aid is not only feasible but highly desirable. The results obtained are readily interpretable and provide good and meaningful insight into the problem.

The results obtained during the investigation of the program performance show that a complicated but well formulated problem can be solved with ease, and the solution is obtained with speed, accuracy and precision.

The entire program is less than 1000 lines, with a total of 9 subroutines. Every effort has been made to keep the program simple yet unambiguous, so that the user has to invest very little time learning how to use it. Effort has also been made to minimize the use of the computer CPU time. However, expenditure of CPU time is to a large measure dependent upon:

- (1) the order of the system.
- (2) the number of iterations used in reaching a solution.

- (3) the type and order of the compensator(s) used.

B. RECOMMENDATIONS

The program as presented in this thesis seems to be able to adequately satisfy the usual needs in a control system design problem. A number of useful extensions to the work developed in this thesis can be carried out. These are briefly discussed.

1. Curve Fitting

Although not specifically worked on in this thesis, the program can be used quite effectively for curve fitting purposes. This was demonstrated in the initial stages of the development of this program. The procedure is, by its very nature, iterative and therefore time consuming and cumbersome. However, the entire algorithm can be automated using a minimization subroutine, with the program outputting a polynomial to fit a given curve over a specified range of the independent variable.

2. Computer Selection of Compensators

A suitable minimization routine such as Box PLX can be incorporated into the program which could select the best possible location of poles and zeroes to meet given performance specifications. This would automate the entire Bode design procedure, the user then having the option of only specifying the type of compensation, i.e., cascade or feedback. It may however be pointed out that minimization

routines by the very nature of their operation are very time consuming and wasteful of CPU resources.

3. Root Locus

Most of the subroutines developed in this thesis are very general in nature and can be adapted quite easily to develop a similar interactive program for Root Locus plots.

4. Integrated Control System Design

No meaningful design of control systems is complete without finally analyzing its time domain performance. It is therefore considered highly desirable to incorporate into this program, an interactive Root Locus design procedure and then a time domain analysis of the compensated system. The entire package would then be an excellent teaching aid for control system design.

APPENDIX PROGRAM LISTING

NUM000010
NUM000020
NUM000030
NUM000040
NUM000050
NUM000060
NUM000070
NUM000080
NUM000090
NUM000100
NUM000110
NUM000120
NUM000130
NUM000140
NUM000150
NUM000160
NUM000170
NUM000180
NUM000190
NUM000200
NUM000210
NUM000220
NUM000230
NUM000240
NUM000250
NUM000260
NUM000270
NUM000280
NUM000290
NUM000300
NUM000310
NUM000320
NUM000330
NUM000340
NUM000350
NUM000360
NUM000370
NUM000380
NUM000390
NUM000400
NUM000410
NUM000420
NUM000430
NUM000440
NUM000450
NUM000460
NUM000470
NUM000480

```

SUBROUTINE NUMER (NA)
** *****
** SUBROUTINE TO INPUT THE NUMERATOR **
** OF THE PLANT TRANSFER FUNCTION **
** *****
** VARIABLE DECLARATIONS ***
INTEGER ANSWER,YES
REAL NA
DIMENSION NA(10)
DATA YES/.Y./
DO 301 I=1,10
NA(I) = 0.0
CONTINUE
CALL FRTCMS('CLRSCRN')
WRITE(6,351)
READ(5,376)N
WRITE(6,352)N
READ(5,377)ANSWER
IF (ANSWER.EQ. YES)GO TO 302
GO TO 301
CONTINUE
N=N+1
CONTINUE
CALL FRTCMS('CLRSCRN')
WRITE(6,360)
DO 306 I=1,N
J=I-1
WRITE (6,353) J
READ (5,378,END = 305) NA(I)
GO TO 306
REIND 5
CALL FRTCMS ('CLRSCRN')
WRITE(5,356)
GO TO 304
CONTINUE
CALL FRTCMS('CLRSCRN')
DO 307 I = 1,N
J = N-I
K = J+1
WRITE(6,354) J,NA(K)
CONTINUE
WRITE(6,355)
READ(5,379)ANSWER
IF (ANSWER.EQ.YES) GO TO 308.

```



```

C C C C C C
SUBROUTINE FETCH (FENUM)
*****
* SUBROUTINE TO INPUT THE LOWER LIMIT *
* OF THE FREQUENCY AXIS. *
*****
** VARIABLE DECLARATIONS **
INTEGER FENUM,YES,ANSWER
DATA YES/'Y'/

C 01
CONTINUE
WRITE (6,51)
READ (5,76)END = 02) FENUM
CALL FRICMS (0,CLSCRN0)
GO TO C3
REMAIN 5
CALL FRICMS (0,CLSCRN0)
WRITE (6,52)
GO TO C1
CONTINUE
WRITE (6,53)FENUM
READ (5,77)ANSWER
IF (ANSWER.EQ.YES)GO TO 04
CONTINUE
RETURN

C 02
C 03
C 04
C ***** WRITE FORMAT STATEMENTS *****
51 FORMAT(' ',//,4X,' ENTER THE LOWER LIMIT OF THE FREQUENCY AXIS',
*
* AS FOLLOWS: ',//,26X,' FOR EXAMPLE -02.',//,8X,
* IF LOWER LIMIT IS 10**(-02), ENTER -02.',//,8X,
* IF LOWER LIMIT IS 10**(01), ENTER +11.',
* FORMAT(//,7X,' YOU HAVE PRESSED "ENTER" WITHOUT ENTERING ANY ',
* NUMBER.',//,7X,' TRY AGAIN.')
52 FORMAT(//,4X,' THE LOWER LIMIT IS 10**',13,' CORRECT? (Y/N)')
C ***** READ FORMAT STATEMENTS *****
76 FORMAT(12)
77 FORMAT(A1)
C
END

```

```

FET00010
FET00020
FET00030
FET00040
FET00050
FET00060
FET00070
FET00080
FET00090
FET00100
FET00110
FET00120
FET00130
FET00140
FET00150
FET00160
FET00170
FET00180
FET00190
FET00200
FET00210
FET00220
FET00230
FET00240
FET00250
FET00260
FET00270
FET00280
FET00290
FET00300
FET00310
FET00320
FET00330
FET00340
FET00350
FET00360
FET00370
FET00380
FET00390
FET00400
FET00410
FET00420
FET00430
FET00440

```

[illegible]

SEC00490
SEC00500
SEC00510
SEC00520
SEC00530
SEC00540
SEC00550
SEC00560
SEC00570
SEC00580

```

455      FCRMAT(//,7X, : ARE THE ABOVE COEFFICIENTS CORRECT? (Y/N).)
456      * FCRMAT(//,7X, : YOU HAVE PRESSED "ENTER" WITHOUT ENTERING ANY. ,
          * NUMBER.,/,7X, : TRY AGAIN. :)
C ***** READ FORMAT STATEMENTS *****
C *****
478      FCRMAT(F14.0)
479      FCRMAT(A1)
C      END

```



```

353          FCRMAT(//,7X, ' ENTER COEFFICIENT OF S**(1,12,1,1)')
354          FCRMAT(//, ' COEFFICIENT OF S**(1,12,1,1) : E14.6)
355          FCRMAT(//,7X, ' ARE THE ABOVE COEFFICIENTS CORRECT? (Y/N)')
356          FCRMAT(//,7X, ' YOU HAVE PRESSED "ENTER" WITHOUT ENTERING ANY',
          *      ' NUMBER.//,7X, ' TRY AGAIN.')
C ***** READ FCRMAT STATEMENTS *****
C *****
378          FCRMAT(F14.6)
379          FCRMAT(A1)
C          ENC

```

```

SEC000490
SEC000500
SEC000510
SEC000520
SEC000530
SEC000540
SEC000550
SEC000560
SEC000570
SEC000580
SEC000590
SEC000600

```



```

515 READ (5,578,END 515) CPS(I)
    GO TO 516
    REMING 5
    CALL FRICMS ('CLRSCRN')
    WRITE(5,556)
    GO TO 514
516 CONTINUE
    CALL FRICMS ('CLRSCRN')
    DU 517 I = 1,N
    WRITE(6,564) I,CPS(I)
    CONTINUE
517 WRITE(6,555)
    READ(5,577)ANSWER
    IF (ANSWER.EQ.YES) GO TO 518
    GO TO 508
518 CONTINUE
    CALL FRICMS ('CLRSCRN')
    RETURN

```

```

C***** WRITE FORMAT STATEMENTS *****
551 FORMAT(//,7X,'ENTER NUMBER OF CASCADE FILTERS AS A 1',
    * ,DIGIT INTEGER',
552 * FORMAT(//,7X,11,'CASCADE FILTERS ARE BEING USED',4X,
    * 'CORRECT? (Y/N)',
553 * FORMAT(//,7X,'ENTER ZERO OF FILTER NUMBER',12,
554 * ,ZERO NUMBER',12,
555 * ,E14.6),
556 * FORMAT(//,7X,'ARE THE ABOVE VALUES CORRECT? (Y/N)',
    * ,NUMBER',7X,'YOU HAVE PRESSED "ENTER" WITHOUT ENTERING ANY',
    * ,NUMBER',7X,'TRY AGAIN.',
560 * ,VALUES OF POLES AND ZEROS OF THE CASCADE',
563 * ,FILTERS MUST BE ENTERED',7X,'IN DECIMAL FORMAT',
564 * ,ENTER POLE OF FILTER NUMBER',12,
    * ,POLE NUMBER',12,
    * ,E14.6)
C***** READ FORMAT STATEMENTS *****
570 FORMAT(11)
577 FORMAT(A1)
578 FORMAT(F12.5)
C
    END

```

CAS00490
 CAS00500
 CAS00510
 CAS00520
 CAS00530
 CAS00540
 CAS00550
 CAS00560
 CAS00570
 CAS00580
 CAS00590
 CAS00600
 CAS00610
 CAS00620
 CAS00630
 CAS00640
 CAS00650
 CAS00660
 CAS00670
 CAS00680
 CAS00690
 CAS00700
 CAS00710
 CAS00720
 CAS00730
 CAS00740
 CAS00750
 CAS00760
 CAS00770
 CAS00780
 CAS00790
 CAS00800
 CAS00810
 CAS00820
 CAS00830
 CAS00840
 CAS00850
 CAS00860
 CAS00870
 CAS00880
 CAS00890
 CAS00900
 CAS00910


```

408      GO TO 403
      CONTINUE
      CALL FRICMS('CLRSCRN')
      RETURN

C***** WRITE FORMAT STATEMENTS *****
451      FURMAT(//,7X,'ENTER ORDER OF DENOMINATOR POLYNOMIAL AS A 1',
452      *      FURMAT(//,7X,'ORDER OF DENOMINATOR POLYNOMIAL IS ',11,4X,
453      *      FURMAT(//,7X,'CORRECT? (Y/N)',)
454      *      FURMAT(//,7X,'ENTER COEFFICIENT OF S**(,12,')',)
455      *      FURMAT(//,7X,'COEFFICIENT OF S**(,12,')',E14.6)
456      *      FURMAT(//,7X,'ARE THE ABOVE COEFFICIENTS CORRECT? (Y/N)',)
460      *      FURMAT(//,7X,'YOU HAVE PRESSED "ENTER" WITHOUT ENTERING ANY',
      *      FURMAT(//,7X,'NUMBER.',/7X,'TRY AGAIN.',)
      *      FURMAT(//,7X,'ALL DENOMINATOR COEFFICIENTS MUST BE ENTERED ',
      *      FURMAT(//,7X,'IN DECIMAL FORMAT.',)

C***** READ FORMAT STATEMENTS *****
476      FURMAT(11)
477      FURMAT(11)
478      FURMAT(F14.4)
479      FURMAT(11)
      END

```

```

DENUC490
DENUC500
DENUC510
DENUC520
DENUC530
DENUC540
DENUC550
DENUC560
DENUC570
DENUC580
DENUC590
DENUC600
DENUC610
DENUC620
DENUC630
DENUC640
DENUC650
DENUC660
DENUC670
DENUC680
DENUC690
DENUC700
DENUC710
DENUC720
DENUC730
DENUC740
DENUC750

```



```

308      GO TO 303
      CONTINUE
      CALL FRTCMS('CLRSCRN')
      RETURN

C***** WRITE FORMAT STATEMENTS *****
351      FORMAT(///,7X,'ENTER ORDER OF NUMERATOR POLYNOMIAL AS A 1',
      *      DIGIT INTEGER')
352      FORMAT(///,7X,'ORDER OF NUMERATOR POLYNOMIAL IS ',I1,4X,
      *      'CORRECT ? (Y/N)')
353      FORMAT(///,7X,'ENTER COEFFICIENT OF S**(',I2,')')
354      FORMAT(///,7X,'COEFFICIENT OF S**(',I2,') : E14.6)
355      FORMAT(///,7X,'ARE THE ABOVE COEFFICIENTS CORRECT? (Y/N)')
356      FORMAT(///,7X,'YOU HAVE PRESSED "ENTER" WITHOUT ENTERING ANY',
      *      'NUMBER.',7X,'TRY AGAIN.')
360      FORMAT(///,7X,'ALL NUMERATOR COEFFICIENTS MUST BE ENTERED ',
      *      'IN DECIMAL FORMAT')

C***** READ FORMAT STATEMENTS *****
376      FORMAT(I1)
377      FORMAT(A1)
378      FORMAT(F14.4)
379      FORMAT(A1)

      END

```

```

NUM0C490
NUM00500
NUM00510
NUM00520
NUM00530
NUM00540
NUM00550
NUM00560
NUM00570
NUM00580
NUM00590
NUM00600
NUM00610
NUM00620
NUM00630
NUM00640
NUM00650
NUM00660
NUM00670
NUM00680
NUM00690
NUM00700
NUM00710
NUM00720
NUM00730
NUM00740
NUM00750

```



```

1002 CALL SECASC(CN1)
      CALL SECASC(CD1)
      CONTINUE
      WRITE(6,1060)
1015 READ(5,1077)ANSWER
      IF(.NOT. ANSWER.EQ.YES)GO TO 1019
      CALL FEECHK(FN,CA,FF)
      CONTINUE
      CALL FETCHF (NUM)
      CALL LECALE(DEC5)
1014 CALL TITLE(TIL,MSS)
      CONTINUE
      ADECS = FLQAT(DEC5)
      WRITE(6,1070)
      READ(5,1076)ANS2
      DO 101 = 1,271
        LOGW(1) = (1-1)/270.*ADECS
        FREQ(1) = (10.0**((LOGW(1)))*(10.** (NUM)))
        S = CMFLX(Z,FREQ(1))
      C***** UNCOMPENSATED SYSTEM : ALMERATOR *****
      C*****
      N = A(1)*(S**0) + A(2)*(S**1) + A(3)*(S**2) + A(4)*(S**3)
        * + A(5)*(S**4) + A(6)*(S**5) + A(7)*(S**6) + A(8)*(S**7)
        * + A(9)*(S**8) + A(10)*(S**9)
      C***** UNCOMPENSATED SYSTEM : DENOMINATOR *****
      C*****
      D = B(1)*(S**0) + B(2)*(S**1) + B(3)*(S**2) + B(4)*(S**3)
        * + B(4)*(S**3) + B(5)*(S**4) + B(6)*(S**5) + B(7)*(S**6)
        * + B(8)*(S**7) + B(9)*(S**8) + B(10)*(S**9)
      HPLANT = N/D
      C***** FIRST ORDER CASCADE FILTERS *****
      C*****
      NCAS = ((S/CZ(1))+1.)*((S/CZ(2))+1.)*((S/CZ(3))+1.)*
        * ((S/CZ(4))+1.)*((S/CZ(5))+1.)*((S/CZ(6))+1.)
      C*****
      DCAS = ((S/CP(1))+1.)*((S/CP(2))+1.)*((S/CP(3))+1.)*
        * ((S/CP(4))+1.)*((S/CP(5))+1.)*((S/CP(6))+1.)
      C*****
      HCAS = NCAS/DCAS
      C*****
      C***** SECOND ORDER CASCADE FILTERS *****
      C*****
      NCAS2 = (CN1(1)*(S**2)+CN1(2)*(S**1)+CN1(1))
        * (CN2(1)*(S**2)+CN2(2)*(S**1)+CN2(1))
      DCAS2 = (CU1(1)*(S**2)+CU1(2)*(S**1)+CU1(1))
        * (CU2(1)*(S**2)+CU2(2)*(S**1)+CU2(1))
      C*****

```

MA100970
MA100980
MA100990
MA101000
MA101010
MA101020
MA101030
MA101040
MA101050
MA101060
MA101070
MA101080
MA101090
MA101100
MA101110
MA101120
MA101130
MA101140
MA101150
MA101160
MA101170
MA101180
MA101190
MA101200
MA101210
MA101220
MA101230
MA101240
MA101250
MA101260
MA101270
MA101280
MA101290
MA101300
MA101310
MA101320
MA101330
MA101340
MA101350
MA101360
MA101370
MA101380
MA101390
MA101400
MA101410
MA101420
MA101430
MA101440

```

SECFIL=NCAS2/DCAS2
***** FEEDBACK COMPENSATION *****
NFBK = FK*(S**FN)
DFBK = (S**DN)+(FP)
HFBK = NFBK/DFBK
H = HPLANT*HCAS*SECFIL
H = H/(1.0 + (HFBK*H))
IF (ANS2.EQ. UPEN) GO TO 1128
H = H/(1.0 + H)
CONTINUE
RE = REAL(H)
AI = AIMAG(H)
PHD = 57.295 * ATAN2(AI,RE)
IF (PHD.GT.0.) PHD = PHD - 360.
PHASE(1) = PHD
HMAG(1) = 20.*ALOG10(CABS(H))
IF (HMAG(1).GT.120.) HMAG(1) = 120.
IF (HMAG(1).LT.-120.) HMAG(1) = -120.
CONTINUE
WRITE(6,1067)
READ(5,1076) ANSWER
IF (.NOT. ANSWER.EQ. YES) GO TO 1999
CALL FRICMS('CLRSCRN')
WRITE(6,1005)
DO 1999 I=1,271.5
WRITE(6,1060) FREQ(I), HMAG(I), PHASE(I)
CONTINUE
CALL TEKOLD
CALL BLOWUP(1.2)
CALL PAGE(11,8.5)
CALL NCCHER
CALL AREA2D(9,16.)
CALL XNAME('FREQUENCY (RAD. PER SEC)',100)
CALL YNAME('TRANSFER FUNCTION (MAG)',100)
CALL HEADIN('TTL,20,1.5,2')
CALL HEADIN('MS,20,1.5,2')
CALL XLUG('FREQ(1),9./ADELS,-60.00,20.1)
CALL LINES('PHASE',IPAK,2)
CALL LINES('GAIN',IPAK,1)
XW=XLUGND(IPAK,2)
YW=YLEUGND(IPAK,2)
XL=8. - .5-XW-.1
YL=6. - .5-YW-.1
CALL BLNK1(XL-.3,0.-.4,YL-.3,6.-.4,2)
CALL LINESP(3.5)
CALL DOT

```

MAI 01420
 MAI 01430
 MAI 01440
 MAI 01450
 MAI 01460
 MAI 01470
 MAI 01480
 MAI 01490
 MAI 01500
 MAI 01510
 MAI 01520
 MAI 01530
 MAI 01540
 MAI 01550
 MAI 01560
 MAI 01570
 MAI 01580
 MAI 01590
 MAI 01600
 MAI 01610
 MAI 01620
 MAI 01630
 MAI 01640
 MAI 01650
 MAI 01660
 MAI 01670
 MAI 01680
 MAI 01690
 MAI 01700
 MAI 01710
 MAI 01720
 MAI 01730
 MAI 01740
 MAI 01750
 MAI 01760
 MAI 01770
 MAI 01780
 MAI 01790
 MAI 01800
 MAI 01810
 MAI 01820
 MAI 01830
 MAI 01840
 MAI 01850
 MAI 01860
 MAI 01870
 MAI 01880
 MAI 01890
 MAI 01900
 MAI 01910
 MAI 01920

CALL GRID(1,2)
 CALL RESET(.03T.)
 CALL THKCRV(.015)
 CALL LEGLIN
 CALL CURVE(FREQ,HMA6,271,0)
 CALL YGRAXS(-360,.60,0.0.5.,PHASE\$, -100,9.0,0.0.)
 CALL DOT
 CALL LEGLIN
 CALL CURVE(FREQ,PHASE,271,0)
 CALL RESET(.015)
 CALL RESET(.THKCRV.)
 CALL LEGEND(IPAK,2,XL,YL)
 CALL ENDPL(0)
 WRITE(6,1051)
 READ(5,1076) ANSWER
 IF(.NOT.ANSWER.EQ. YES) GO TO 1006

 1018 CONTINUE
 WRITE(6,1053)
 READ(5,1076)ANS
 CALL FRICMS(.CLRS CRN.)
 IF(ANS.EQ.CHP)GO TO 1014
 IF(ANS.EQ.CHW)GO TO 1010
 IF(ANS.EQ.CHL)GO TO 1011
 IF(ANS.EQ.CHC)GO TO 1012
 IF(ANS.EQ.CHY)GO TO 1017
 IF(ANS.EQ.CHN)GO TO 1124
 IF(ANS.EQ.CHD)GO TO 1125
 IF(ANS.EQ.CHS)GO TO 1126
 IF(ANS.EQ.CHF)GO TO 1127
 CALL DECADE(DECS)
 GO TO 1015
 CALL FETCH(NUM)
 GO TO 1015
 CALL CASCAD(CZ,CP)
 GO TO 1015
 CALL TTLES(TTL,MSS)
 GO TO 1015
 CALL NUMBER(A)
 GO TO 1015
 CALL DENUM(B)
 GO TO 1015
 CALL SECAS(CN1)
 CALL SECAS(CD1)
 GO TO 1015
 CALL FEEDBK(FK, FN, D,FP)
 WRITE(6,1055)
 READ(5,1076)ANS1

MAI01930
MAI01940
MAI01950
MAI01960
MAI01970
MAI01980
MAI01990
MAI02000
MAI02010
MAI02020
MAI02030
MAI02040
MAI02050
MAI02060
MAI02070
MAI02080
MAI02090
MAI02100
MAI02110
MAI02120
MAI02130
MAI02140
MAI02150
MAI02160
MAI02170
MAI02180
MAI02190
MAI02200
MAI02210
MAI02220
MAI02230
MAI02240
MAI02250
MAI02260
MAI02270
MAI02280
MAI02290
MAI02300
MAI02310
MAI02320
MAI02330
MAI02340
MAI02350
MAI02360
MAI02370

```

1006 IF(.NOT.ANS1.EQ.YES)GO TO 1014
      GO TO 1018
      CONTINUE
      WRITE(6,1057)
      READ(5,1076)ANSWER
      IF(ANSWER.EQ.YES)GO TO 1025
      CALL DUNEPL
      STOP
1051 FFORMAT(///,7X,' DO YOU WISH TO HAVE ANOTHER RUN OF THE SAME',
      * PRBLEM (Y/N),, CATERGORIES FOR CHANGES AS FOLLOWS :',/,7X,
1053 FFORMAT(//,7X,' ENTER IN NUMERATOR OF PLANT TRANSFER FUNCTION',/,7X,
      * N CHANGE IN DENOMINATOR OF PLANT TRANSFER FUNCTION',/,7X,
      * D CHANGE IN DECADES TO BE SPANNED',/,7X,
      * W NUMBER OF DECADES TO BE SPANNED',/,7X,
      * L LOWER LIMIT OF FREQUENCY AXIS',/,7X,
      * C CHANGE IN FIRST ORDER CASCADE FILTERS',/,7X,
      * T TITLES',/,7X,
      * S CHANGE IN SECOND ORDER CASCADE FILTER',/,7X,
      * F CHANGE IN FEEDBACK COMPENSATION',/,7X,
      * P NO CHANGES.,)
1052 FFORMAT(//,7X,' ANY FIRST ORDER CASCADE COMPENSATORS? (Y/N)',)
1055 FFORMAT(//,7X,' ANY MORE CHANGES? (Y/N)',)
1056 FFORMAT(//,7X,' ANY SECOND ORDER CASCADE FILTERS? (Y/N)',)
1057 FFORMAT(//,7X,' DO YOU WISH TO RUN A NEW PROBLEM? (Y/N)',)
1060 FFORMAT(//,7X,' ANY FEEDBACK COMPENSATION? (Y/N)',)
1065 FFORMAT(//,7X,' FREQ., 15X, MAGNITUDE., 10X, PHASE',/,/,)
1056 FFORMAT(4X,E14.6,5X,E14.6,5X,E14.6)
1057 FFORMAT(//,7X,' DO YOU WANT TABULAR OUTPUT AT THE TERMINAL?',
      * 4X, (Y/N),)
1070 FFORMAT(//,7X,' DO YOU WANT OPEN OR CLOSE LOOP RESPONSE?',/,7X,
      * ENTER U FOR OPEN LOOP.,/,12X, C FOR CLOSE LOOP.,)
1072 FFORMAT(///,7X,' BOPLT IS AN EASY, INTERACTIVE METHOD TO PRODUCE',
      * OPEN AND CLOSE LOOP.,/,7X, BODE PLOTS. THE TRANSFER',
      * FUNCTION DATA AND PARAMETERS OF CASCADE AND/OR.,/,7X,
      * FEEDBACK COMPENSATORS ARE TO BE ENTERED MANUALLY',
      * AT THE KEYBOARD.,/,7X, IF YOU WANT A PRINT-JOB',
      * THE TABULAR RESULTS, USE THE "RECORD ON",/,7X,
      * "RECORD OFF" EXEC. YOU SHOULD BE LOGGED IN AT THE',
      * IBM 3277/TEK 618.,/,7X, DUAL SCREEN TERMINALS.,
      * ///,/,/,/,)
1076 FFORMAT(AI)
1077 FFORMAT(AI)
1078 FFORMAT(AI)
      END

```

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